1962-09-01

A pressure control system for a hypersonic wind tunnel.

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A PRESSURE CONTROL SYSTEM FOR A HYPERSONIC WIND TUNNEL

A THESIS

SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS AND THE COMMITTEE OF THE GRADUATE DIVISION OF STANFORD UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

ENGINEER

BY

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SEPTEMBER 1962

CONTENTS

LIST OF ILLUSTRATIONS

ACKNOWLEDGMENT

The author wishes to express his appreciation for the guidance and many helpful suggestions received from his advisor, W. H. Horton of the Department of Aeronautics and Astronautics of Stanford University. The readily available counseling, day or night, made it possible for this project to be completed in the time available. Appreciation is also expressed to the wind tunnel personnel for their capable assistance in the installation and checking out of equipment and systems associated with this project.

I. INTRODUCTION

In the past few decades man's exploration of space has developed from a few high altitude rocket probes to earth orbiting of manned vehicles. With this increase in space exploration the problems of high speed flight and the associated heating and aerodynamic loading, particularly those involving re-entry into the earth's atmosphere, have become the object of considerable study. Extensive experimental as well as theoretical investigations are required. One means for studying the effects of high speed flight, particularly when the problem can be investigated on a small scale, is a high temperature hypersonic wind tunnel. Such facilities are used to investigate the thermal stress in structures and the ablation of materials under simulated re-entry conditions. They are clearly capable of either manual or automatic control. It is unfortunate that, unless the operating crew has had considerable training and experience, manual control leads to somewhat eratic behavior and a lack of repeatability. Thus, it is highly desirable that the system should, as far as possible, be automatic. This paper describes the design and installation of an automatic pressure control system built for the Stanford University hypersonic structural wind tunnel and completed in September 1962.

II. TEST FACILITY

The test facility at Stanford University is of the standard blow-down type. A block diagram of the complete system is shown in Fig. 1. It is clear from this block diagram that the system consists of an air compressor and a storage vessel, a regenerative gas fired heat exchanger, and the hypersonic nozzle and tunnel interconnected by the air flow control system. The method of operation of the system is as follows: the air is compressed by the compressors and stored in the storage vessel while the gas fired regenerative heat exchanger is being brought up to temperature. When both these cycles have been completed, the system is ready to operate. At this stage, the gas burner system is sealed off from the gas fired heat exchanger and air fed through from the storage vessel via the air flow control system. From the regenerative gas fired heat exchanger, the air passes through the hypersonic nozzle into the tunnel.

III. DETAILS OF THE AIR STORAGE SYSTEM

Air is compressed to a maximum pressure of 3,000 psi by two Hardie-Tyne compressors which can be run singularly or in parallel. Each unit is capable of producing 30 cubic feet per hour of air compressed to 3,000 psi. The air so compressed is stored in a spherical pressure vessel of 104 cubic feet capacity. The complete charging time, i.e., time to pump the pressure vessel from ambient to full capacity is approximately one and three-quarters hours.

IV. REGENERATIVE GAS FIRED HEAT EXCHANGER

In view of the fact that the system is designed to operate at a maximum stagnation temperature of 4,000 degrees R, heating of the air is accomplished by means of a gas fired regenerative heater shown in cross section in Fig. 2. The storage bed is heated by a natural gas excess air burner positioned at the top of the heat exchanger. Hot gases are forced down through the storage bed and exhausted to the atmosphere through an 8 inch diameter stack. An 8 inch diameter Cammeron valve pneumatically or hydralically operated is fitted in the stack to close during the blow down cycle. This valve is capable of withstanding a maximum pressure of 2,000 psi at a maximum temperature of 650 degrees F. The tunnel instrumentation system is so arranged that the valve can also be used as a dump valve in cases of emergency resulting from malfunction of the control system. The pebble bed, the active part of the heat exchanger, consists in the main of ceramic spheres contained in a cylindrical volume, 14 inches in diameter and 150 inches long. It is shown in the cross section of Fig. 2 that for the first 6 inches the spheres are three-quarter inch diameter zirconium oxide and for the next 108 inches they are three-eights diameter zirconium oxide spheres. The lower 36 inches is made of three-quarters inch diameter aluminium oxide spheres. The pebble bed is supported on a stainless steel grate which is water cooled. At the top of the bed there is a combustion chamber 14 inches in diameter and 60 inches long. The containing wall for the pebble bed is made from pressed zirconium oxide bricks. This layer of refractory brick is surrounded by a layer of less dense refractory and a layer of insulating brick. The heater vessel itself is made from carbon steel and is 56 inches outside diameter and 48 inches inside diameter.

V. AIR FLOW CONTROL SYSTEM

The air flow control system is shown in Fig. 3. It can be seen from this diagram that the system consists of an air control valve, a hydraulic power supply, a hydraulic servo valve, a servo amplifier and a computer controller together with the necessary pressure sensing system to supply information and feedback data to the computer controller. Full details of these components are given in the subsequent paragraphs.

VI. AIR CONTROL VALVES

Air is admitted to the heat exchanger from the storage vessel through parallel one and two inch lines. The air control valves in these lines are of Hammel-Dahl manufacture. The valve in the one inch line is actuated by a Hannifin hydraulic cylinder of 2 inch bore and 2 inch stroke. It will pass a maximum of 0.5 pounds of air per second. The valve in the two inch line is actuated by a Hannifin hydraulic cylinder of 3 1/4 inch bore and 3 inch stroke and will pass a maximum of 3 pounds of air per second.

VII. HYDRAULIC SYSTEM

The hydraulic system for controlling the position of the valve and thus the air flow in the 2 inch air line is shown in Fig. 3. This system was modified to include a servo valve. The servo valve chosen for this installation was a Vickers SA-4-03/1.5/220-10. It can handle flow rates from 0 to 37 gallons per minute. The valve consists basically of a ported block

with 2 spools. One spool, the control spool, is used for controlling the position of the other, the main spool. The main spool directs the flow of fluid to either side of the piston in the Hannifin hydraulic cylinder that controls the air valve in the 2 inch line. The control spool is positioned by the armature of a torque motor. The torque motor receives its command from a servo amplifier located in the control room. The derivation of this signal is discussed in detail in a later section of the paper. A separate source of control pressure is used to reduce load fluctuations on the spool. The recommended value of this pressure is 750 psi. The main line pressure is 1500 psi and the reduced and isolated control pressure is obtained from this by a bang-bang system. This system operates as follows: the control pressure line is connected to an accumulator, which has a pressure actuated valve in its inlet line. This valve opens and closes to maintain the pressure in the accumulator at 750 psi ± 25 psi. To avoid chatter in the system the inlet line is also throttled.

VIII. SERVO AMPLIFIER

The servo amplifier is a Vicker model E 2030-160-3 push-pull amplifier capable of a differential output current of 40 milliamperes. In the balanced condition, the spool is centered, the valve is closed and the current in each winding of the servo valve torque motor is 25 ma. When the full differential current exists, the valve is wide open. The direction of valve opening is dependent upon the direction of differential flow.

IX. PRESSURE SENSING DEVICES

The pressure in the storage vessel, the pressure in the two-inch inlet line, the pressure at the bottom of the bed, and the pressure in the settling chamber were determined by means of pressure transducers. Three types were constructed.

The first type was made from a circular pipe of about one inch inside diameter and wall thickness of 0.040 pressed into an elliptical section. The active gages were placed on the elliptical section and dummy gages on the non-stressed circular base. The unit was then cased for protection. See Fig. 4. The transducers were calibrated using a dead weight tester and a Sanborn Carrier Amplifier Recorder. Two instruments of this type were made. They are linear to within 3% and have a response time of less than 0.1 seconds. The linearity was improved when the transducer was used with a chopper stabilized operational amplifier with a gain of 1,000. The second type was made by a strain gage bridge on the Bourdon tube of a standard pressure gage. See Fig. 4. The response of these was comparable to that of the elliptical tube type. The third pressure measuring device was a differential gage made to detect small differences between high pressures. This consisted of a 0.016 inch steel plate mounted in a heavy case. The two pressures being compared were fed in on either side of a thin diaphragm. The deflection of this diaphragm is proportional to the differential pressure. This was measured by strain gages. See Fig. 4. The differential pressure transducer was calibrated against a mercury column. Fig. 4 shows the transducers and Fig. 5 through Fig. 7 are their calibration charts.

The transducers described above were used to survey the pressure distribution through the system when it was manually operated. The information so obtained was used as base values for the design of the control computer. The results of the survey are shown in Fig. 8.

X. CONTROL COMPUTER

A. Design Considerations

For the successful operation of the hypersonic facility in its present program, the pressure downstream of the hypersonic nozzle must be maintained at a constant predetermined level. In order to obtain the maximum length of run, this stable level must be attained as rapidly as possible with a minimum of overshoot and without bed flotation. Since the fastest responding pressure is the simplest to control and requires the least compensation in the control system, the inlet air pressure was chosen as the control variable. The system was designed as an error control with derivative compensation in the feedback loop and a set point adjuster for the opening phase. For low bed temperatures the adjuster is used to boost and for high bed temperature to depress the set point for a limited time.

It is a requirement of all automatic systems that failure of any element in the system cannot create a potentially dangerous situation or, if it does, an adequate safety control must be actuated immediately. Thus the system is arranged so that too high a differential pressure across the bed or an excess pressure in the settling chamber causes the dump valve to open and the inlet valve to close.

B. Construction Details

A black diagram of the system is given in Fig. 9. The main elements of the computer are a Kintel differential D. C. amplifier and Philbrick plug-in amplifiers, type K2XA. These amplifier systems have high input and low output impedances and were chosen because of their excellent overall performance. The Kintel has a drift stability of better than one microvolt per day, a 1% gain accuracy and 100-cycle bandwidth. The drift rate of the K2XA is $\pm$ 8 millivolt per day and the rise time one microsecond.

C. Modus Operandi of the Analogue Control

The basic function of the analogue controller is to position control the main air inlet valve and thus control the air pressure in the pebble bed. By adjustment of the gain controls in the main and feedback loops, it is possible to restrict the initial differential and to limit the degree of overshoot. The length of run time is adjusted by a time delay relay. Details of system are given in Fig. 9a and b.

Before the blow-down cycle can be instigated the following steps must be completed: (1) the gas burner must be turned off and the shell purged, (2) the gas , air and oxygen lines must be sealed against internal pressure, (3) the stack valve must be closed, (4) the stack valve pneumatic actuation system must be up to pressure, (5) the hydraulic control system pressure must be up to minimum value. The completion of these steps causes a master control switch in the blow-down control system to close and it is now possible to operate the blow-down cycle using the autocontroller. To do this, the desired operating pressure is set and the set point adjuster trimmed for the conditions of operation. The length of run is set on the variable thermal relay.

The blow-down sequence is started by closing a single switch. This step causes the recorders to start, energizes the throat cooling valve solenoid and after five-second delay, during which the adjuster circuit capacitor is charged, the relay in the set point selector circuit closes, the system is fully energized and control operation begins.

The analogue controller compares the existing pressure in the two-inch line with the desired or set point pressure. The servo amplifier and valve convert the error voltage to the appropriate valve opening. Stability is achieved by a rate term. It was found in the design and construction of the controller that a true differentiator produced noise which the servo valve and recording equipment could not tolerate. As a result, a mathematical approximation, being investigated as part of a general research program in derivative circuits, was adopted. The test results show that this circuit gave the desired system stability. The Stability of the servo system is dependant upon a rate term in order to avoid programing the opening phase.

In the operation of the system, it was found that the runs at a lower pressure and temperature would tolerate a more rapid rate of build-up in pressure than was possible with the optimum valves of gain and rate feedback settings. An increased flow of air during the build-up phase was therefore achieved by a "set-point-adjuster" circuit. The adjuster increases the set-point voltage and decreases the time constant by controlled amounts for a limited time but leaves the ultimate set-point voltage unaltered. The higher temperature and pressure runs require a lower rate of pressure build-up and this is controlled by the "set-point adjuster" which in this case temporarily depresses the set-point. Figure 10 shows the console which contains the servo amplifier, its power supply and also the analogue computer.

XI. RESUME OF PERFORMANCE

Fig. 11 shows data for various runs using the analogue controller. Comparison of the data of Fig. 11 with that of Fig. 8 shows clearly the advantages of an automatic pressure control system. The system can be adjusted to obtain optimum operating conditions and the runs can be duplicated. Several runs were made to obtain optimum settings. Data for two pebble bed temperatures are included in Fig. 11. The first is a pebble bed temperature of 500°F and an inlet pressure of 430 and 500 pounds per square inch. The "set-point adjuster" was used to decrease the time to attain stable pressure in the settling chamber. The time was decreased from 13 seconds "unboosted" to 9 seconds "boosted." This is approximately a 30% decrease in pressure build-up time. The second set of operating conditions is a pebble bed temperature of 800°F and an inlet pressure of 550 pounds per square inch. With the higher bed temperature, the time to build up to constant pressure in the setting chamber was 13 seconds. In this case the rate was limited by the differential pressure across the pebble bed.

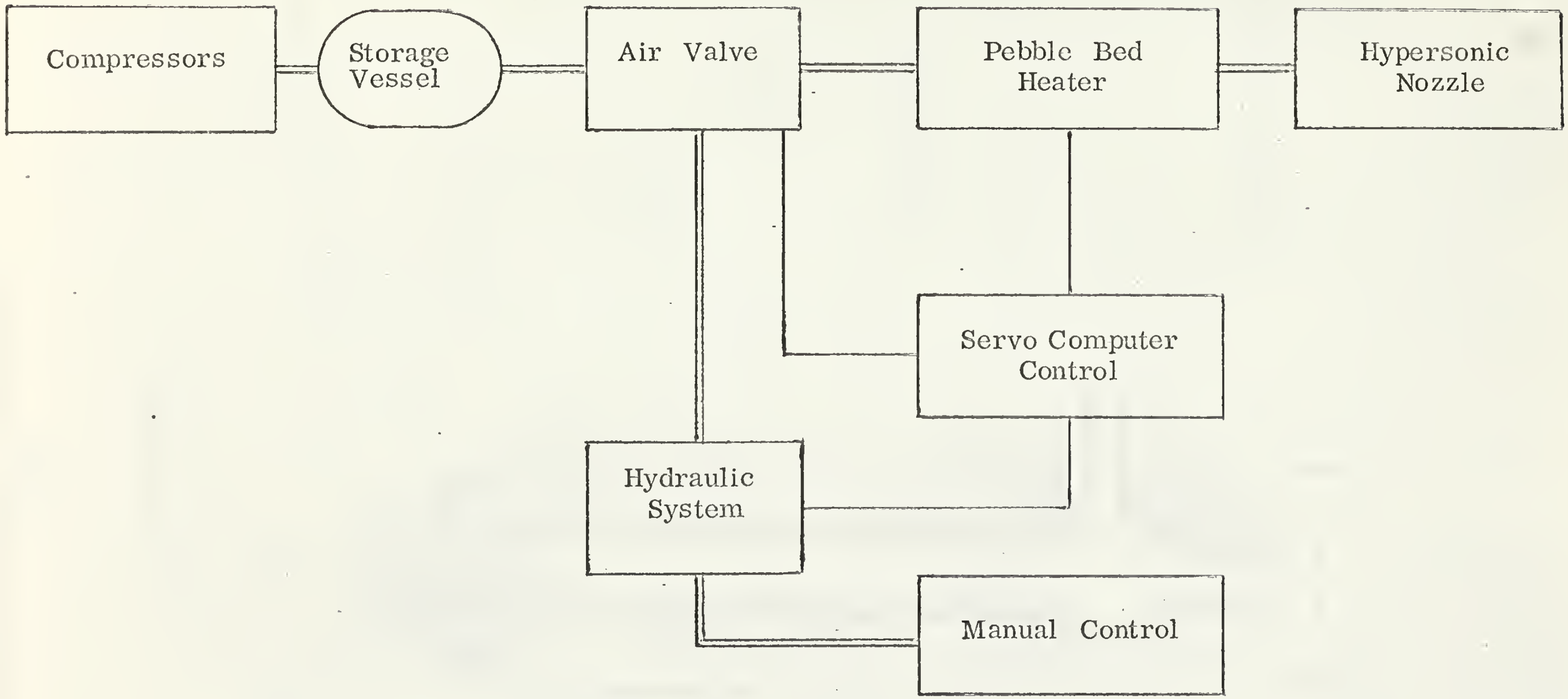
XII. CONCLUDING REMARKS

The present control system for the hypersonic wind tunnel at Stanford University has fulfilled the requirements previously stated, however, there are some additions that would add a further degree of refinement to the system. At present, the pressure transducers used for control are energized by a 10 volt battery and the bridge differential amplifier. This would be improved if a carrier system were obtained to detect the pressure and would give a higher voltage output than the battery method. A function generator with a variable output would extend the limit of testing to simulation of pressure time profiles. This may be advantageous, particularly in the testing of structures. There is at present no connection between the air storage vessel pressure and the control system. A shut down feature for a minimum storage vessel pressure would be desirable.

REFERENCES

Ref. 1. Bloom, Martin H.: A High Temperature-Pressure Air Heater (Suitable for Intermittent Hypersonic Wind - Tunnel Operation), ASME Paper Number 59-A-233.

Ref. 2. Derivative circuits for analog computation and control. (To be published by W. H. Horton and collaborators when research complete.)



Hypersonic Wind Tunnel Components

Figure 1

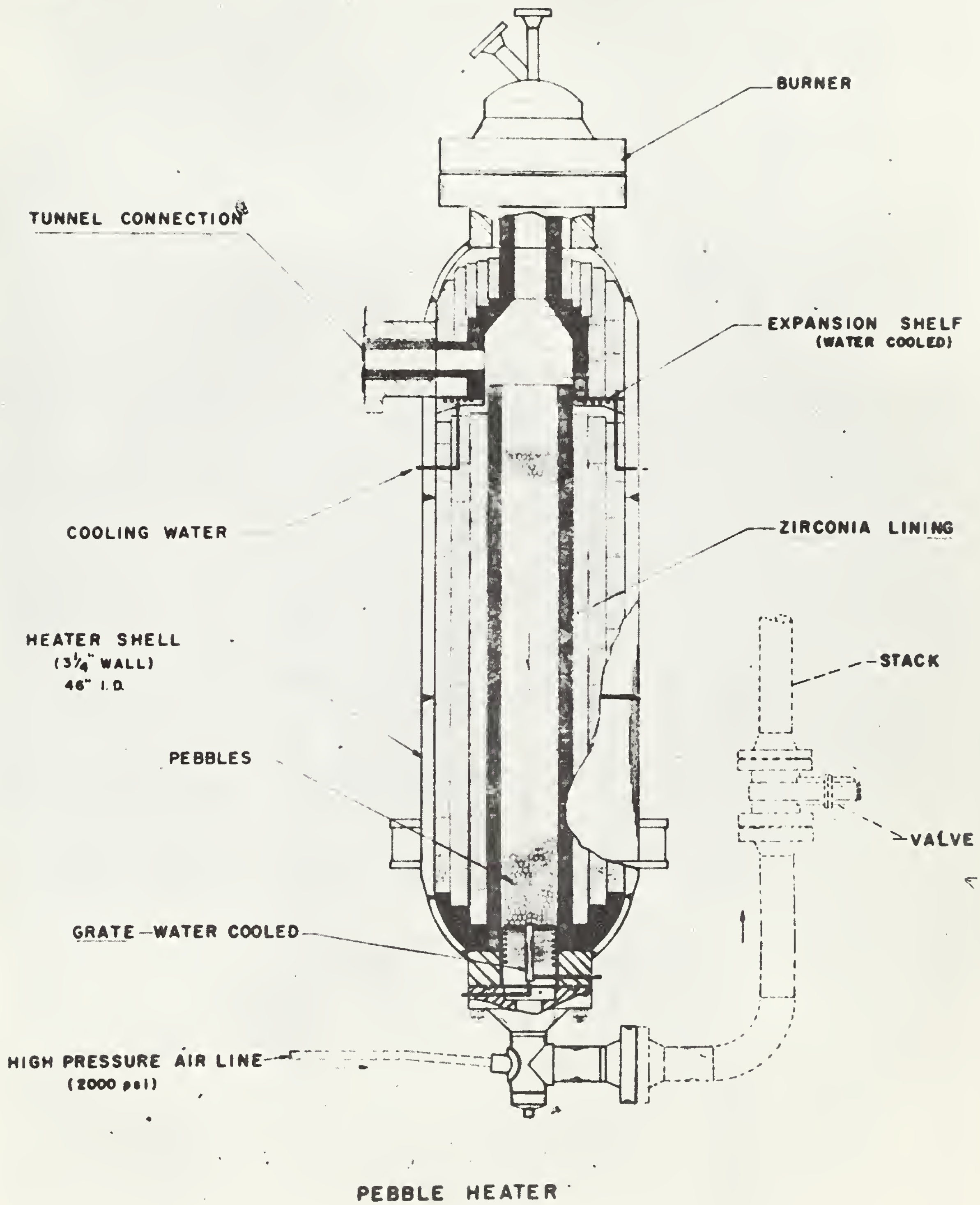
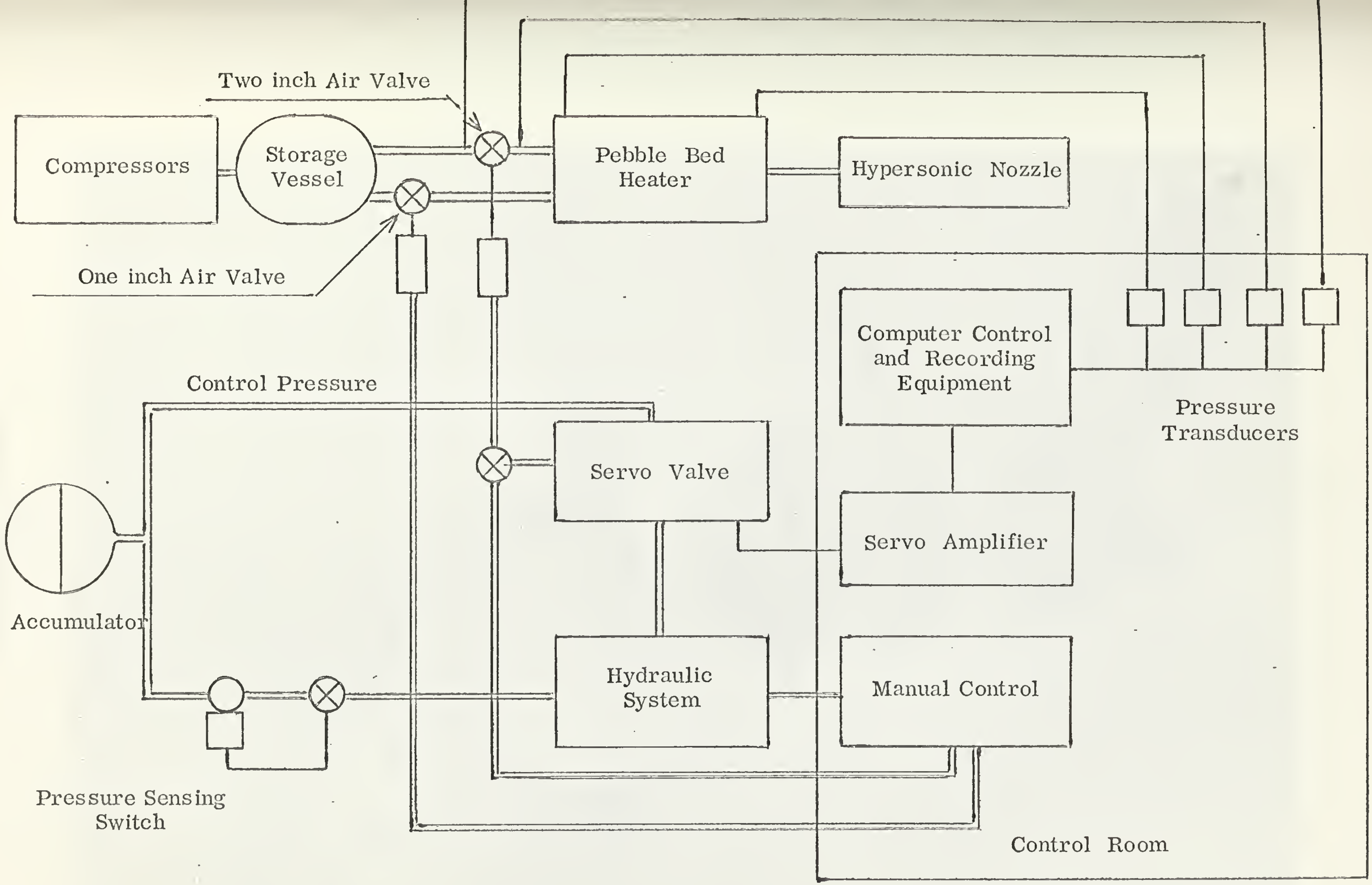


Fig. 2

Cross-Section of the Pebble Heater



Air Flow Control System

Figure 3

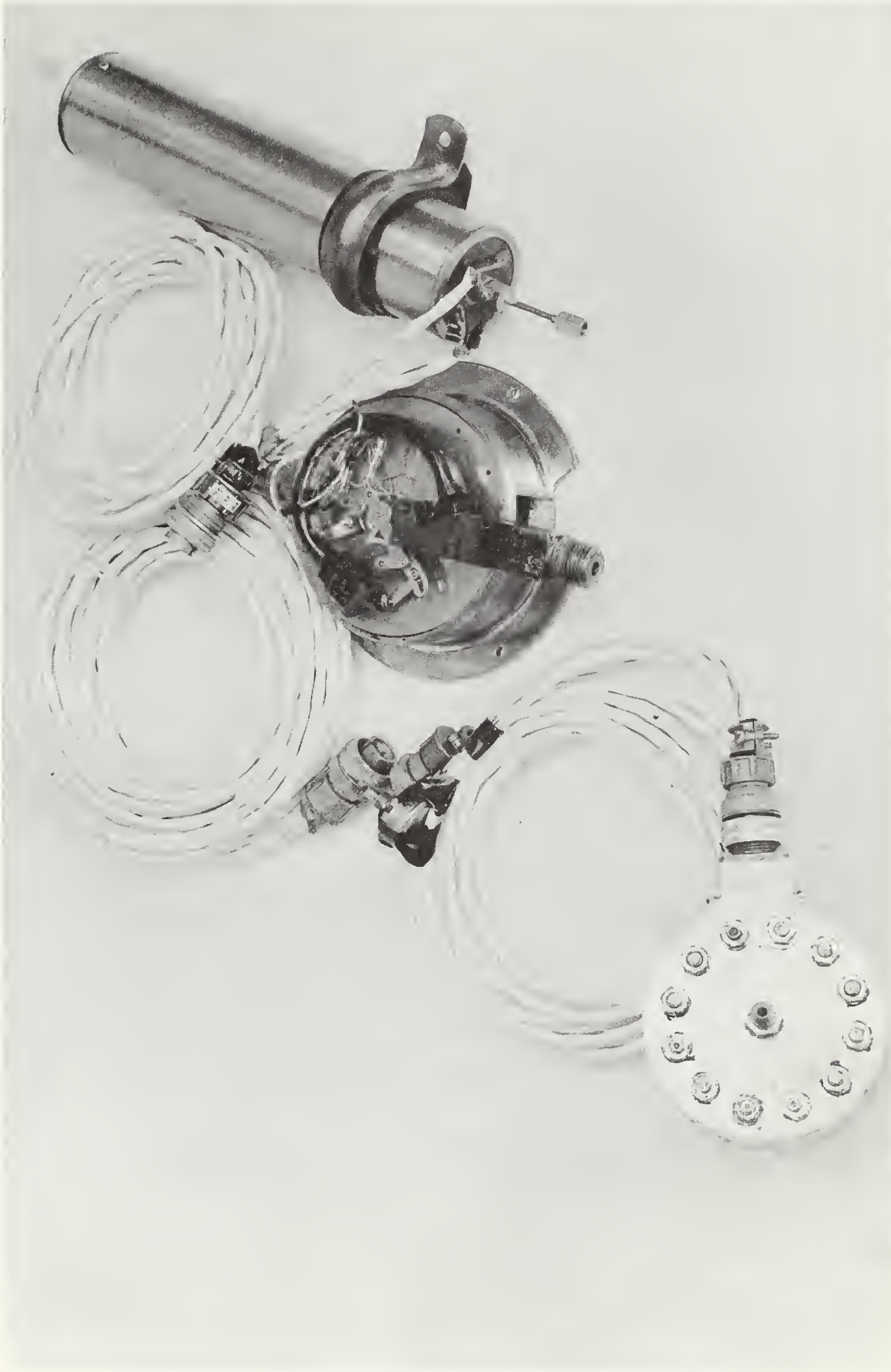


Figure 4

Pressure Transducers

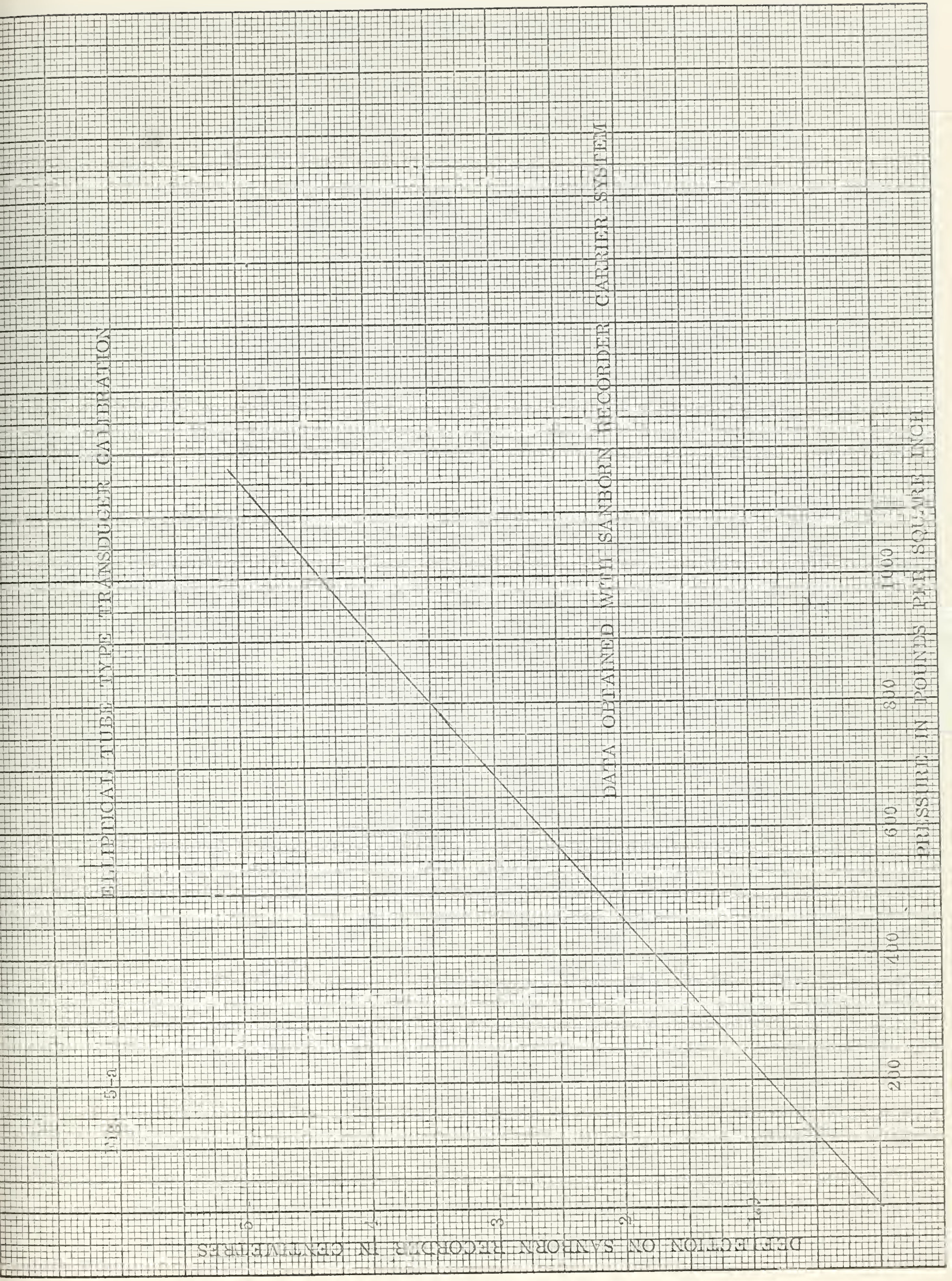


FIG. 5-a ELLIPTICAL TUBE TYPE TRANSDUCER CALIBRATION

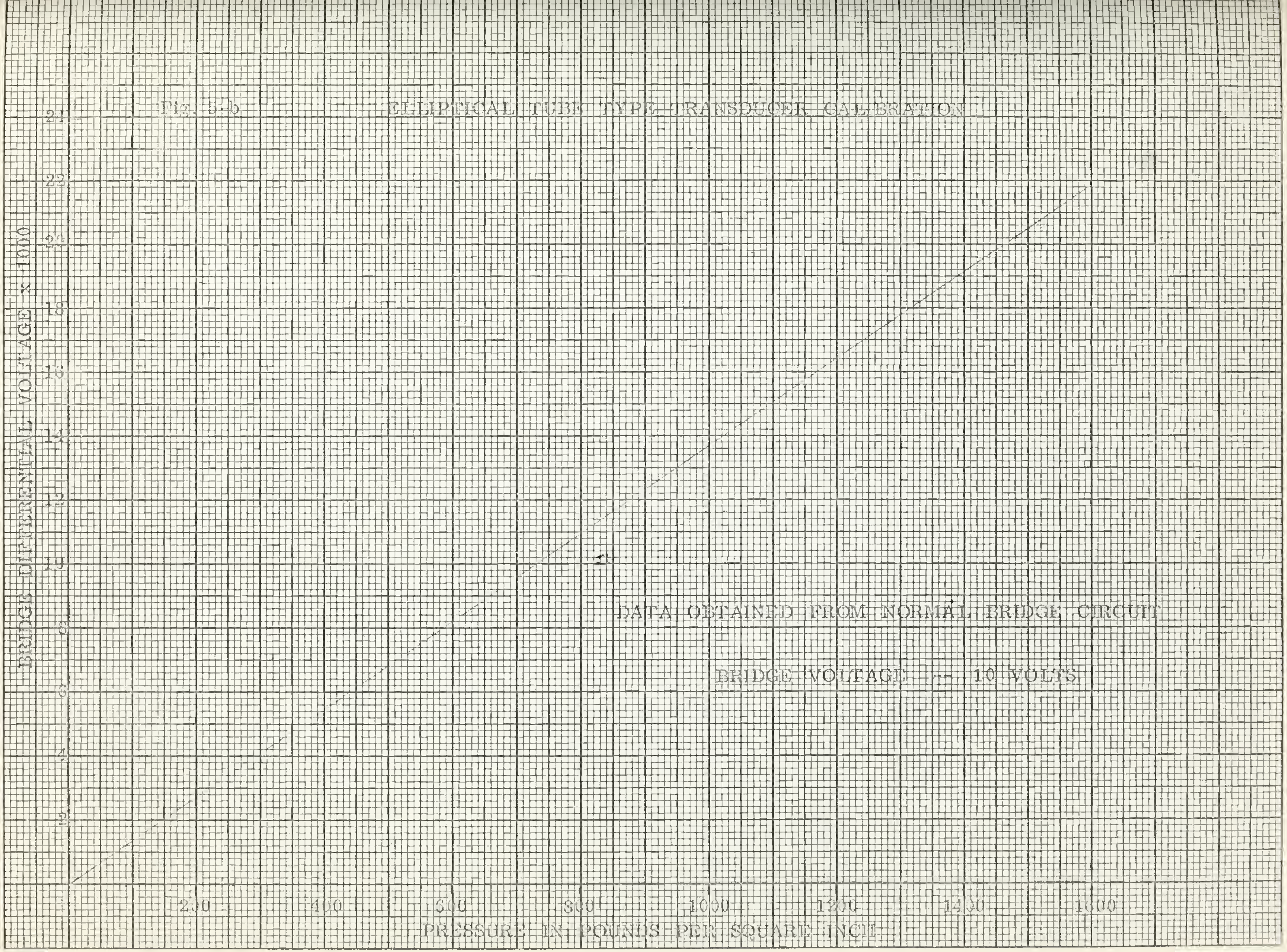


Fig. 5-b ELLIPTICAL TUBE TYPE TRANSDUCER CALIBRATION


Fig. 6 BOURDON TUBE TRANSDUCER CALIBRATION
DATA OBTAINED WITH SANBORN RECORDER CARRIER SYSTEM
DEFLECTION ON SANBORN RECORDER IN CENTIMETRES
0
1
2
3
4
5
200
400
600
800
1000
PRESSURE IN POUNDS PER SQUARE INCH

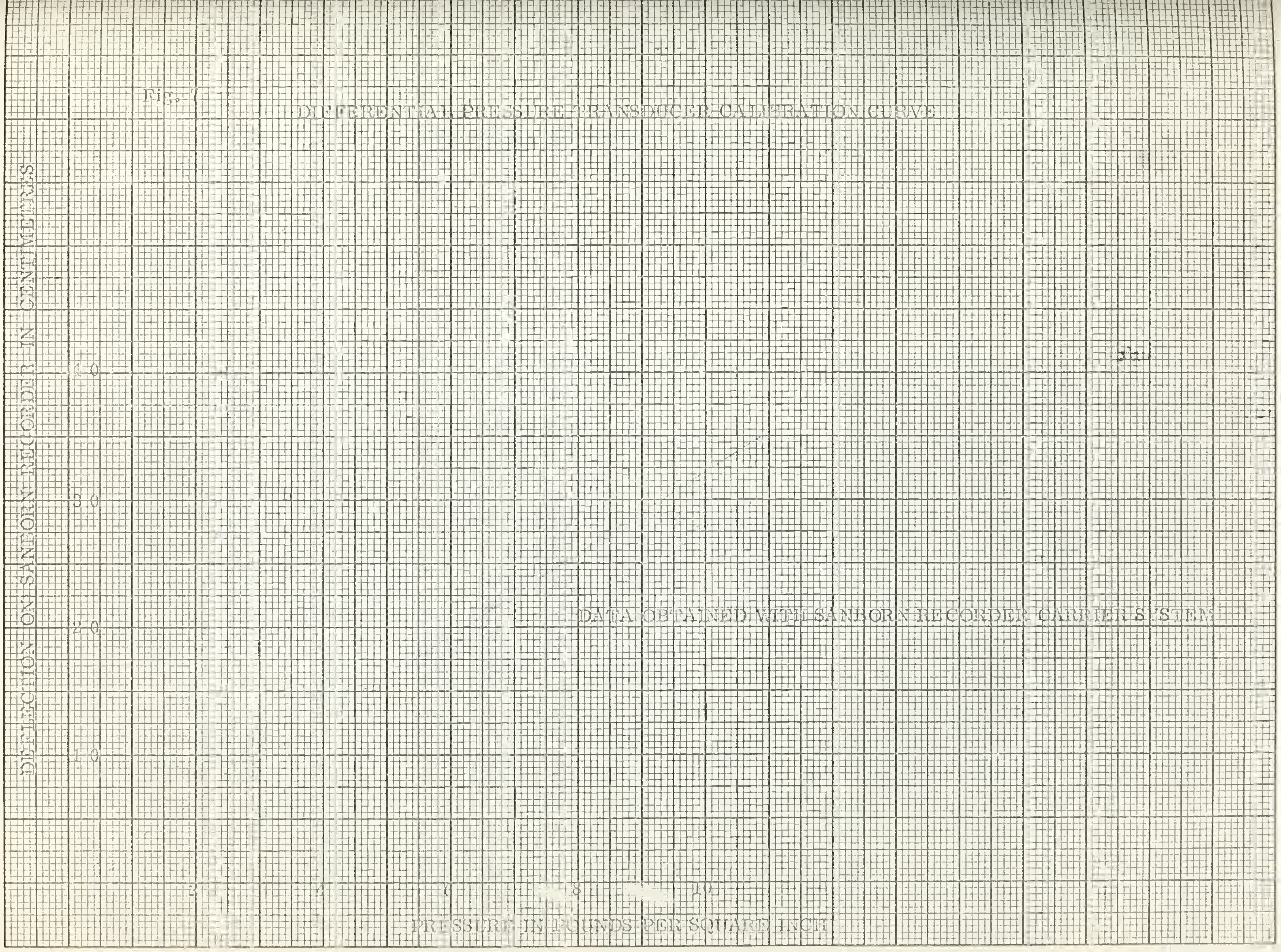


Fig. 7 DIFFERENTIAL PRESSURE TRANSDUCER CALIBRATION CURVE

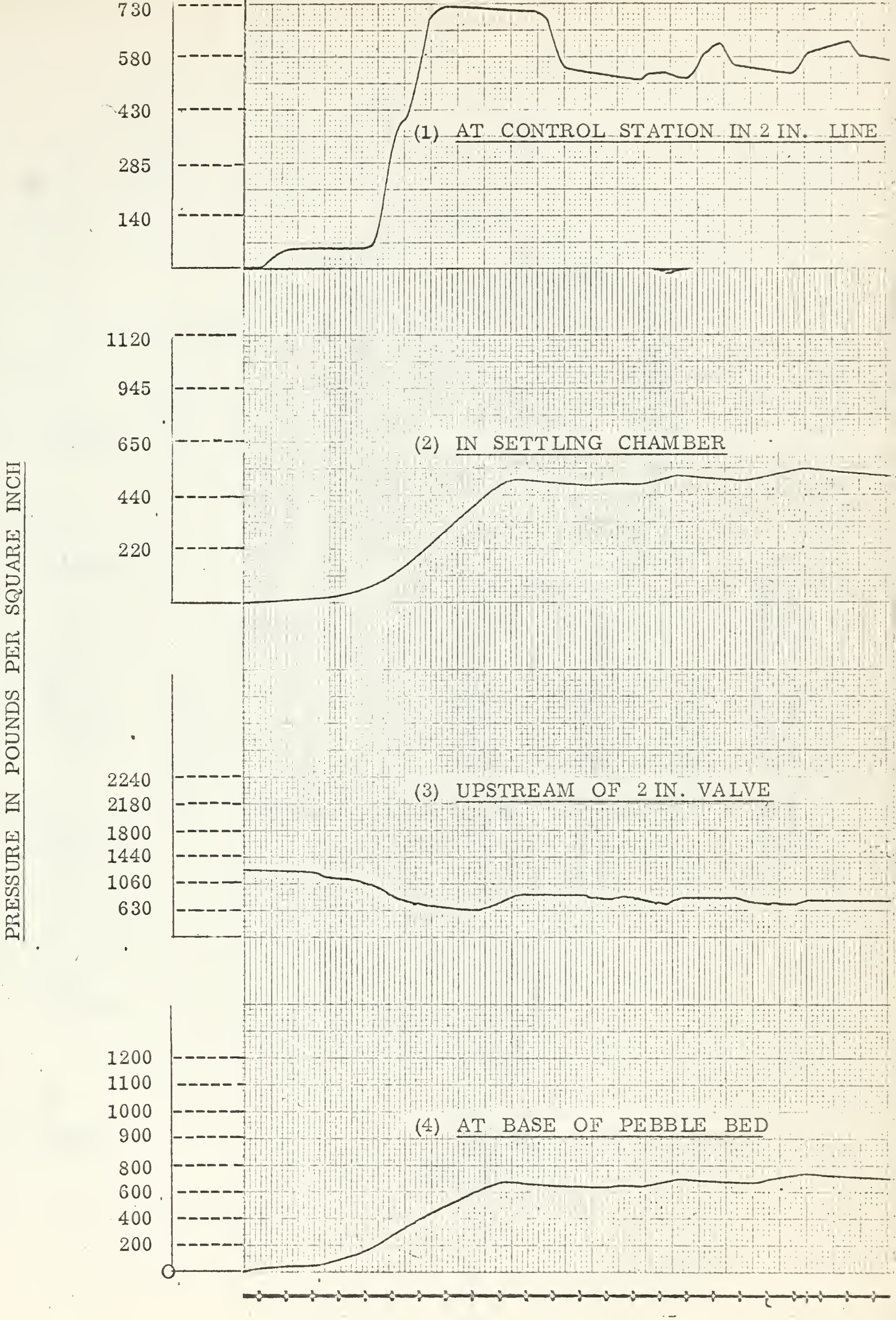


Figure 8

Pressure Survey Utilizing Manual Control

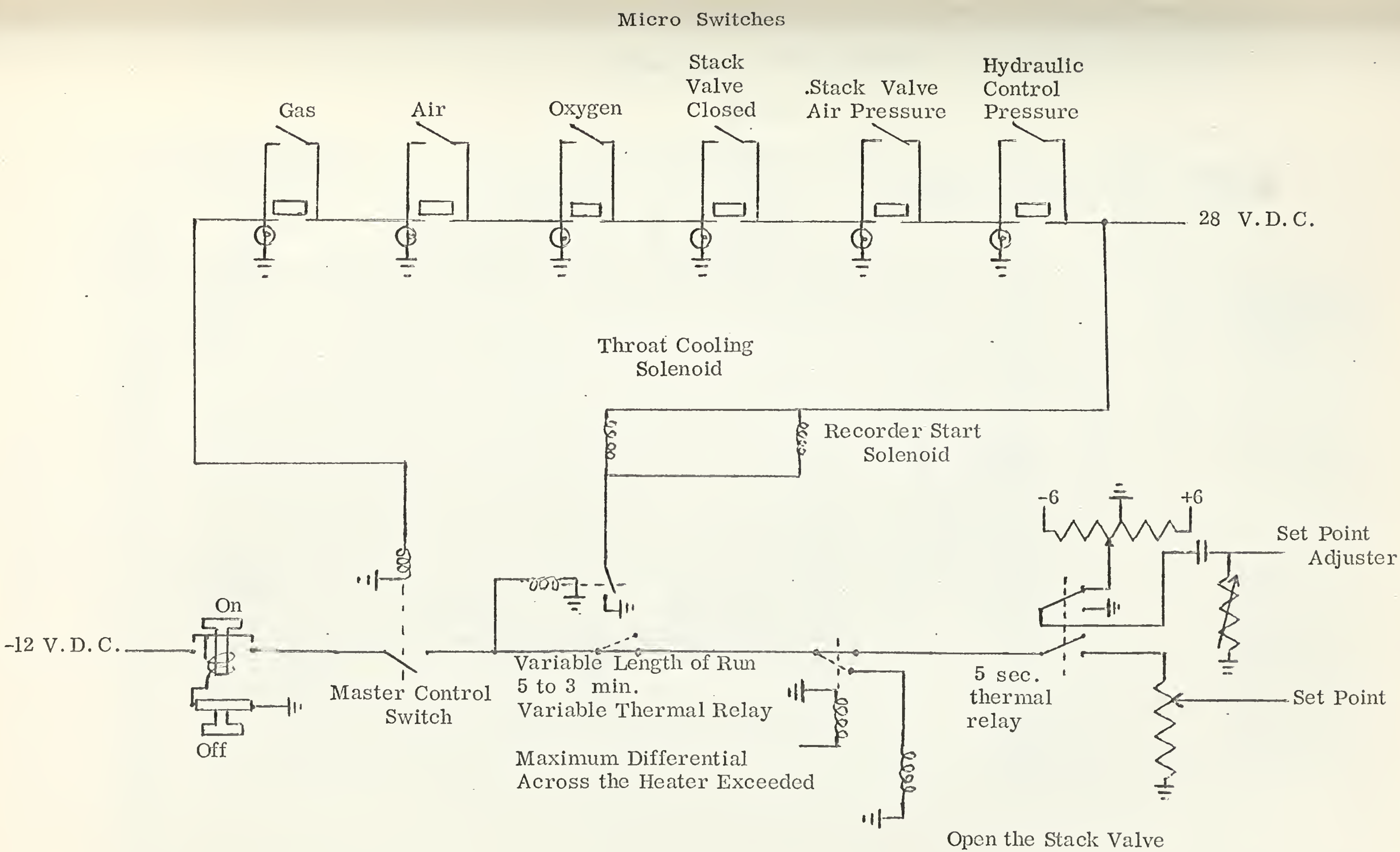


Figure 9 a

Analogue Computer Controller

Starting and Safety Devices

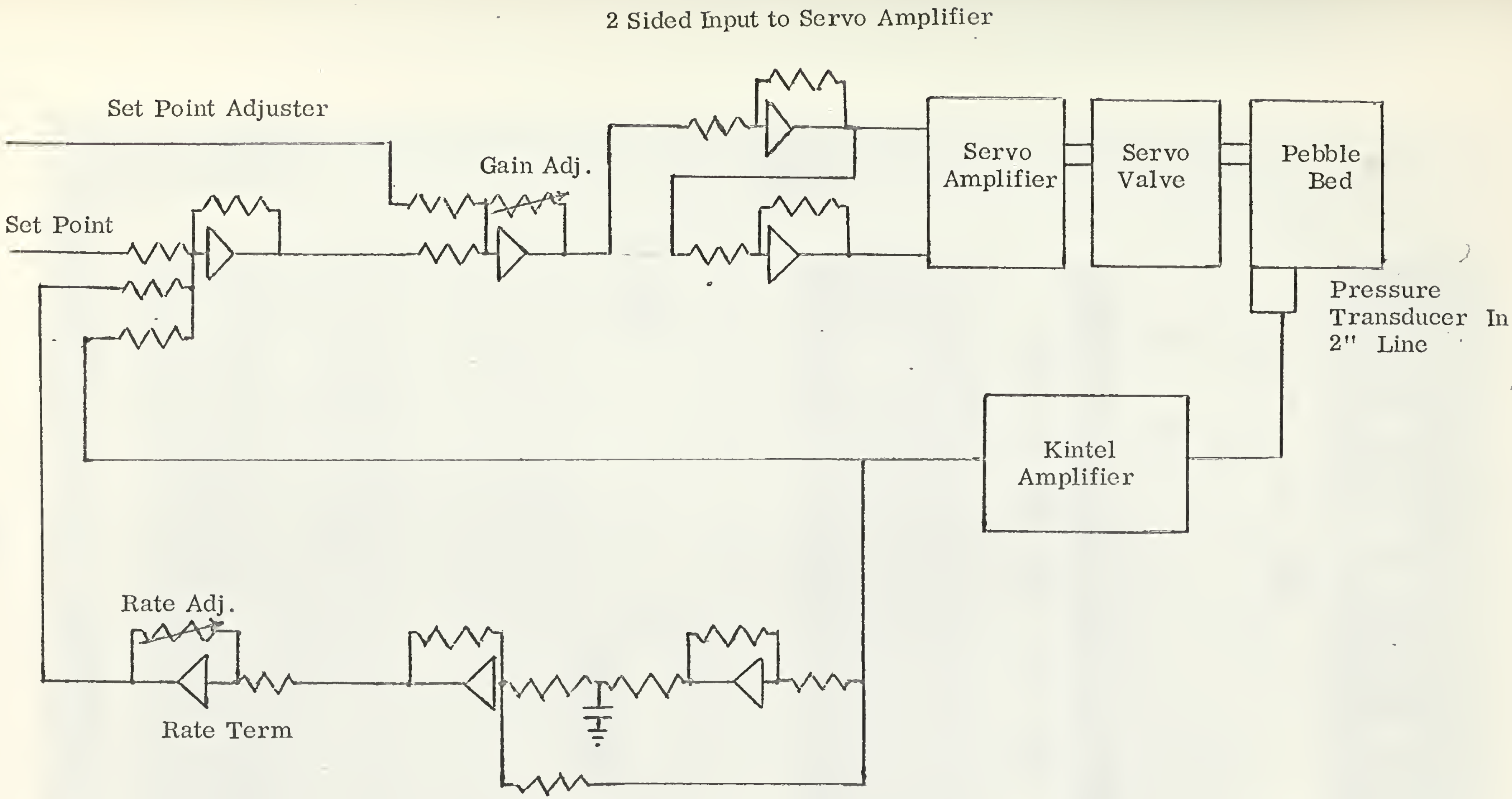


Figure 9 b

Analogue Computer Controller

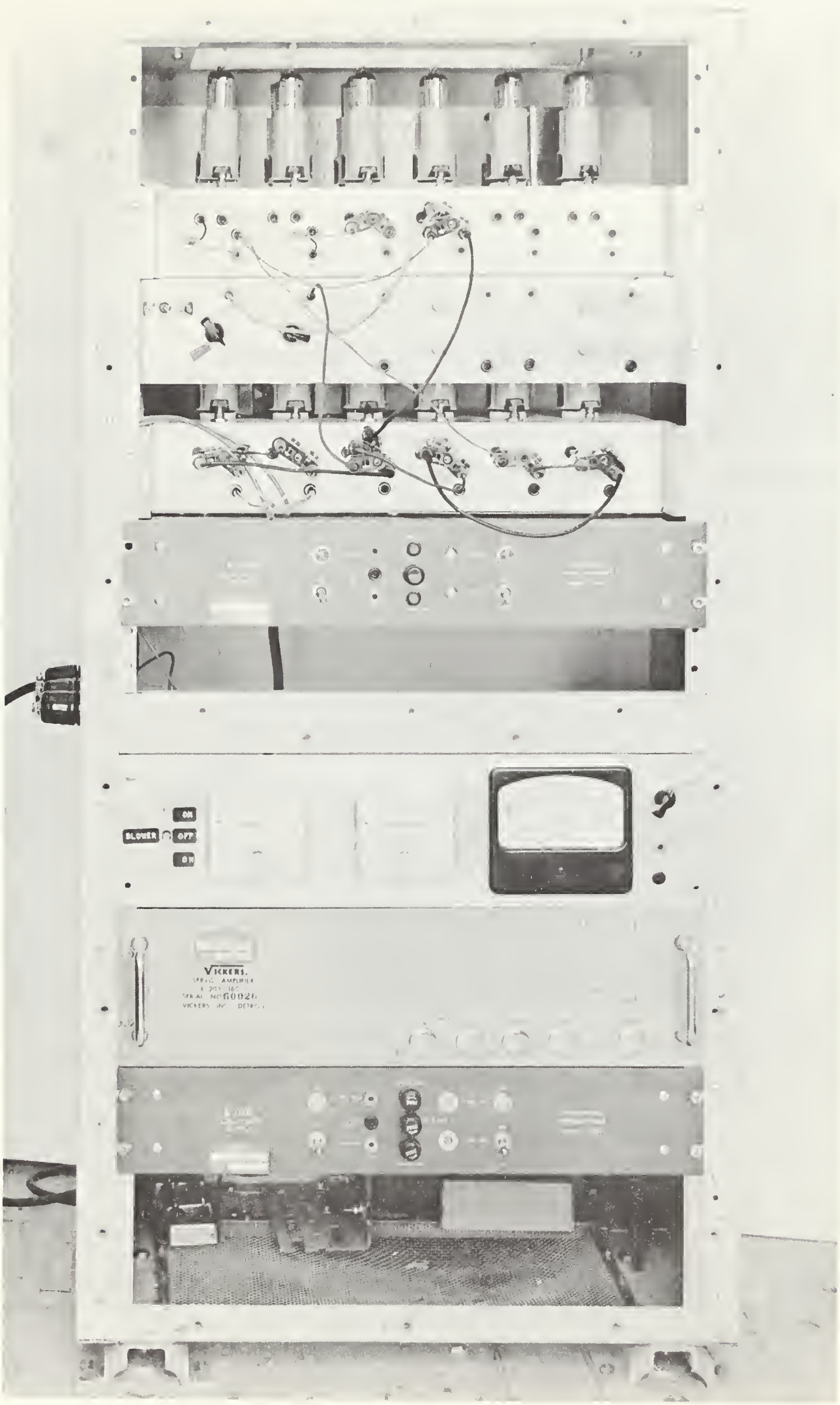


Figure 10

Control Console

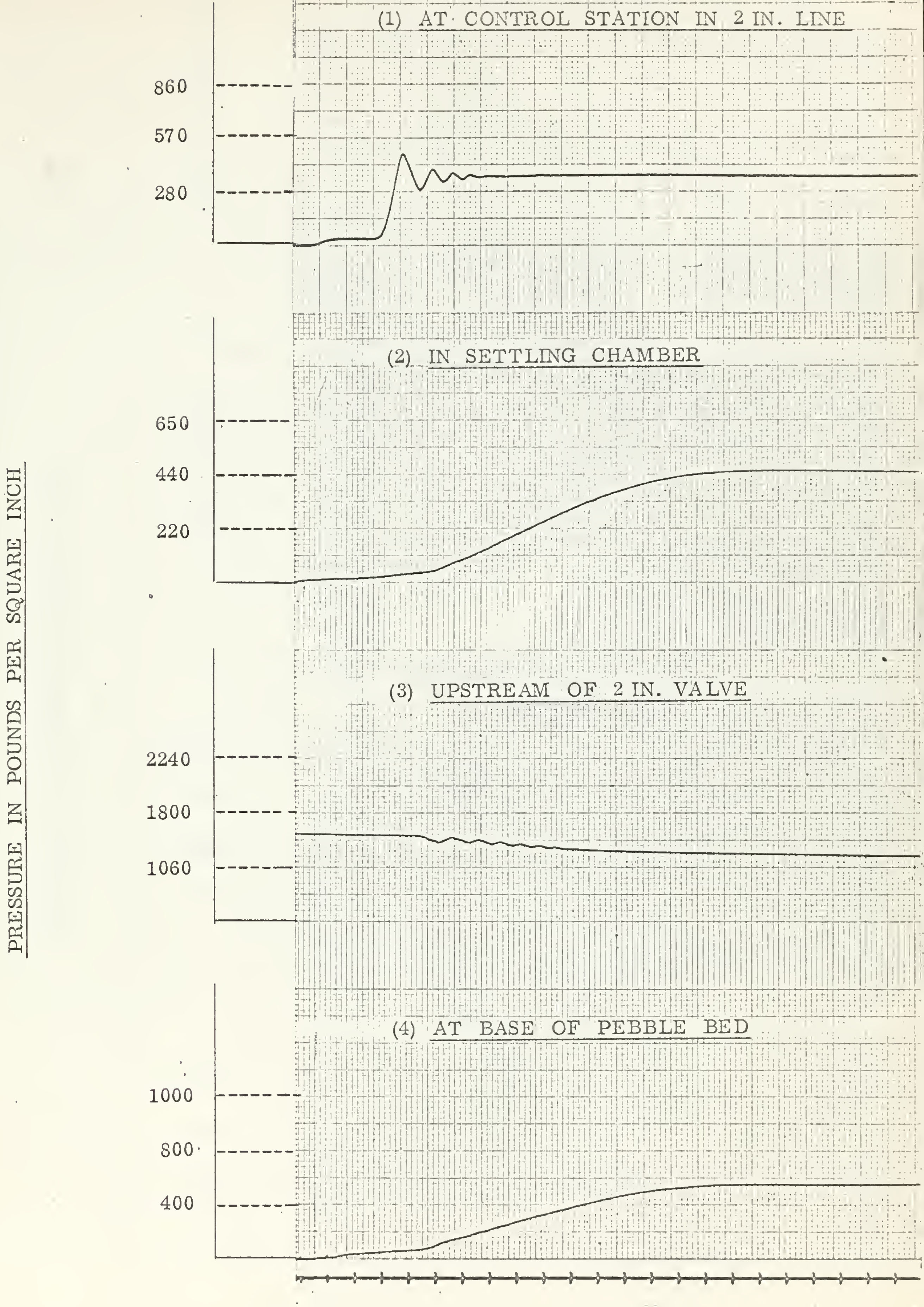


Figure 11 a

Pressure Response Data Using the Controller with Control Set-Point: 430 Pounds p.s.i.
Set-Point Adjuster: 0 Volts
Pebble Bed Temperature: 500° F.

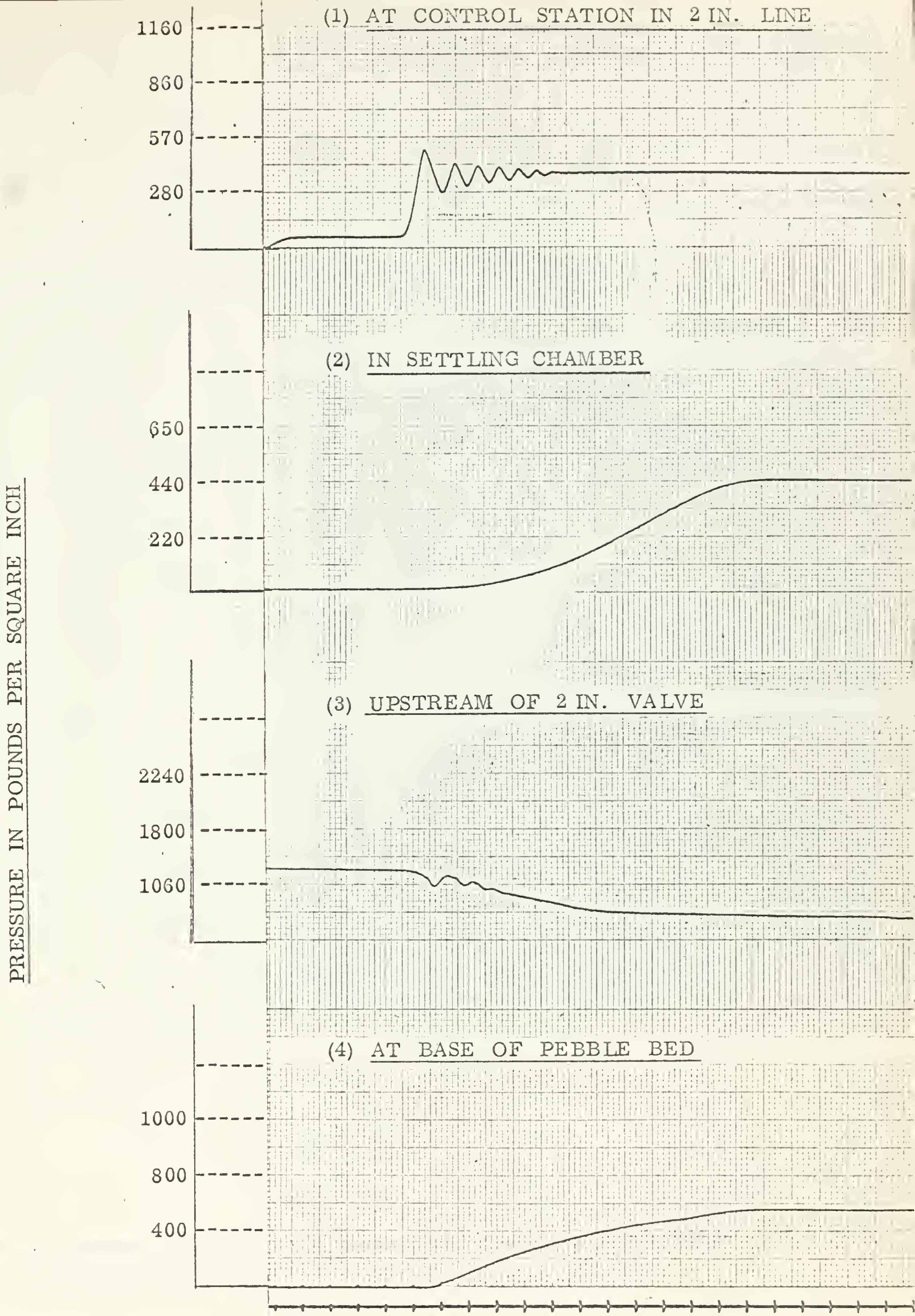


Figure 11 b

Pressure Response Data Using the Controller with Control Set-Point: 430 psi
Set-Point Adjuster: 0 Volts
Pebble Bed Temperature: 500°F.

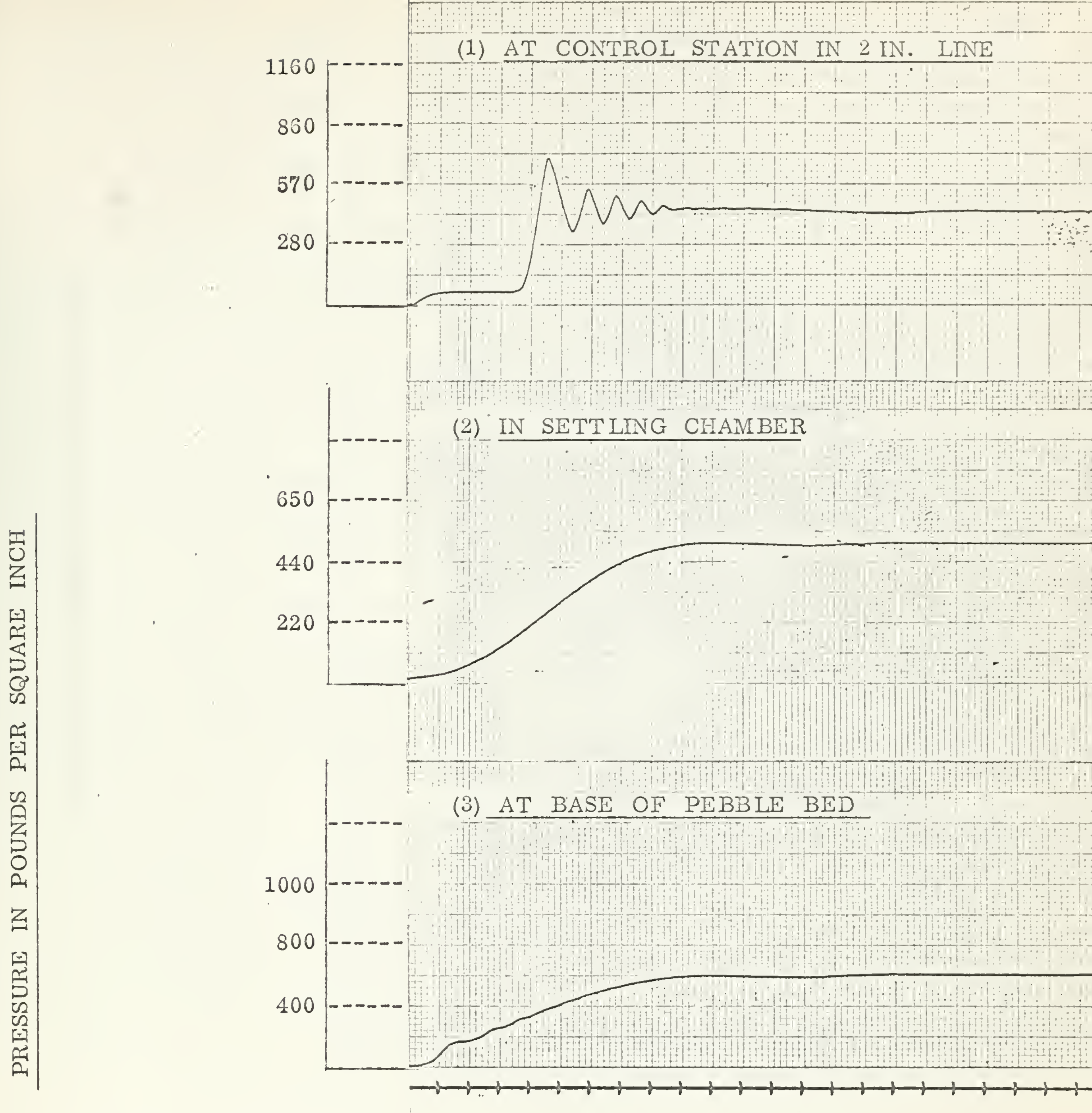


Figure 11 c

Pressure Response Data Using the Controller with Control Set-Point: 500 psi
Set-Point Adjuster: +5 Volts
Pebble Bed Temperature: 500° F.

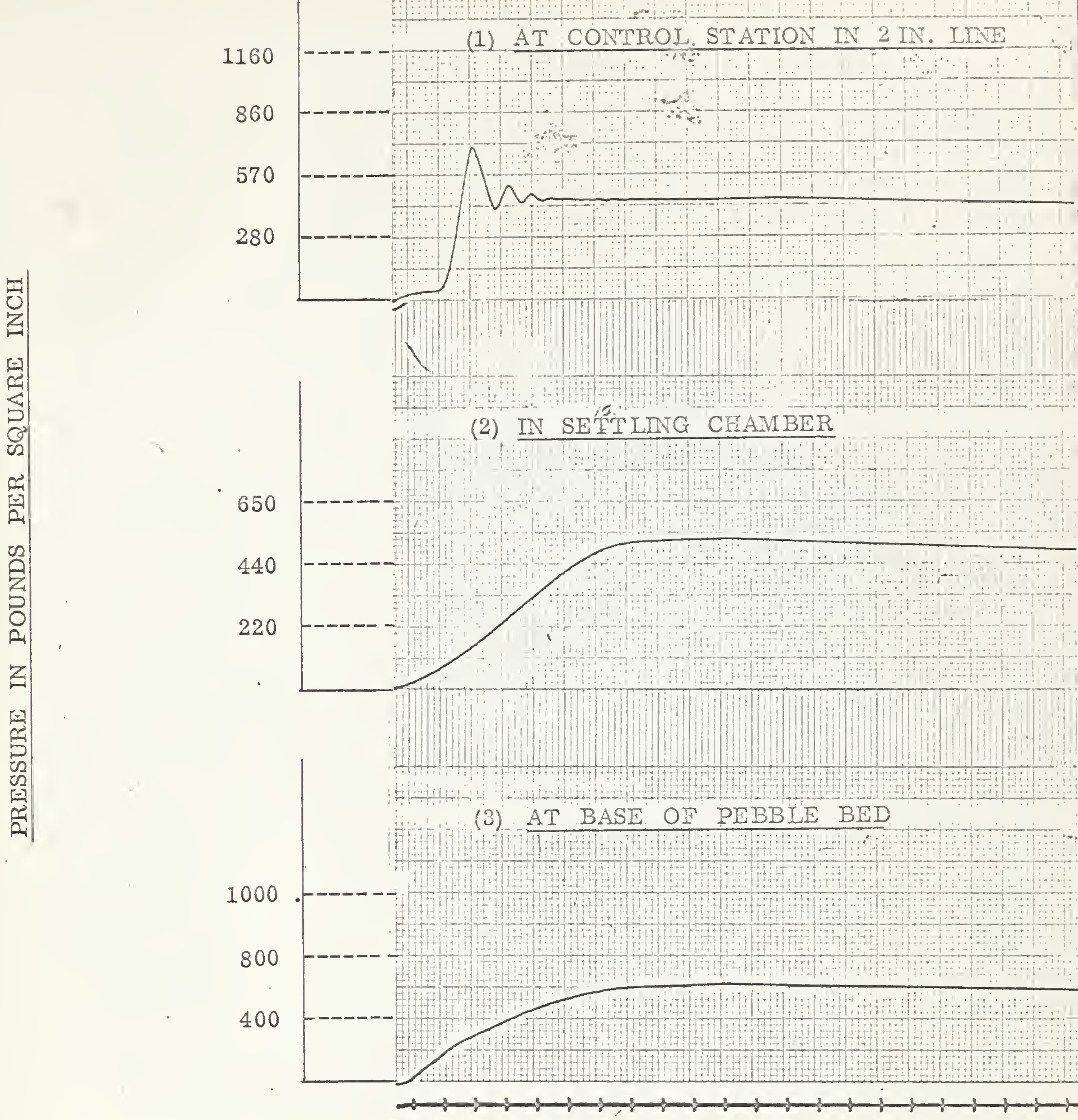


Figure 11 d

Pressure Response Data Using the Controller with Control Set-Point: 500 Pounds p.s.i.
Set-Point Adjuster: + 5 Volts
Pebble Bed Temperature: 500° F.

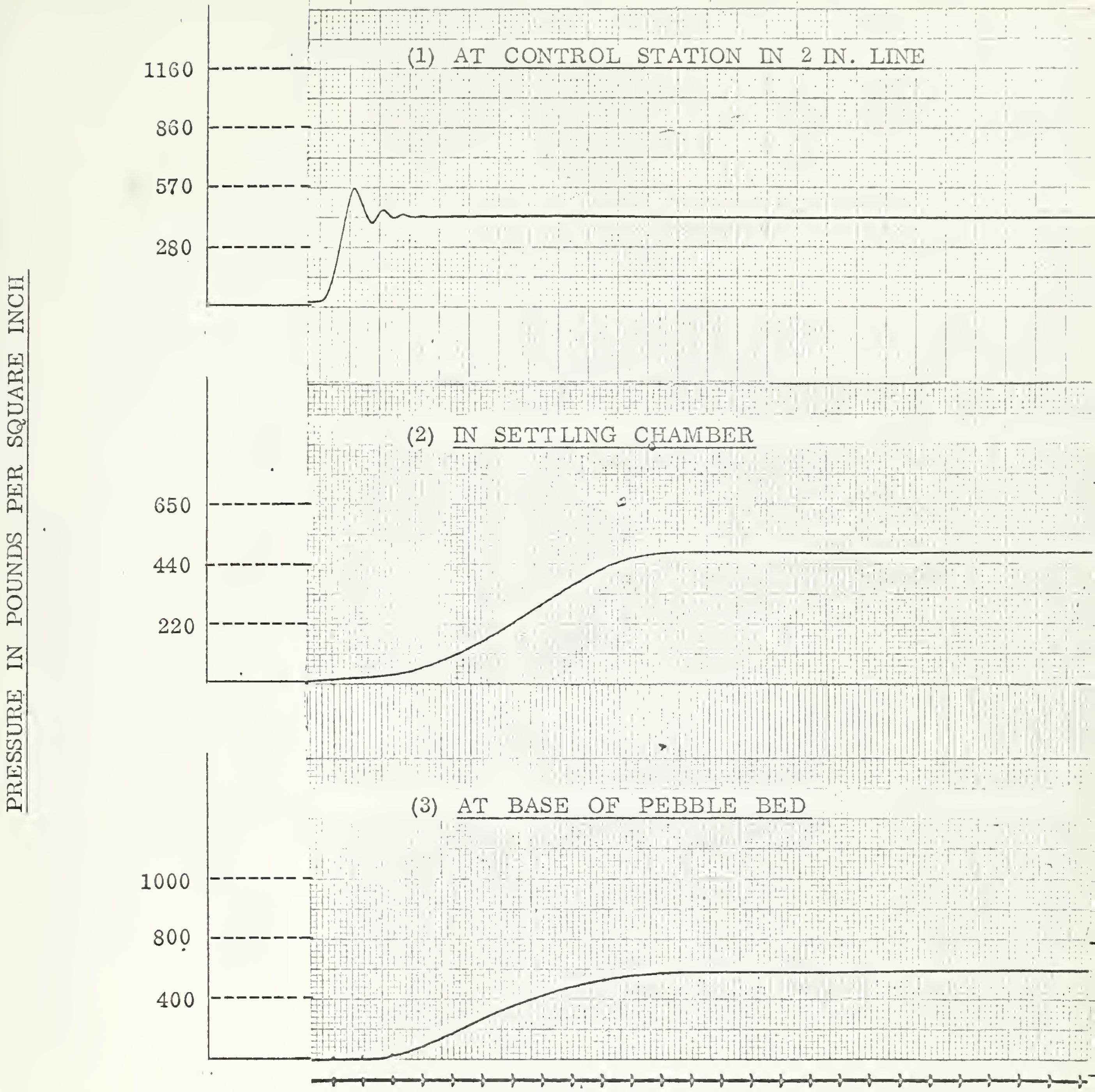


Figure 11 e

Pressure Response Data Using the Controller with Control Set-Point: 500 Pounds p.s.i.
Set-Point Adjuster: + 3 Volts
Pebble Bed Temperature: 500° F.

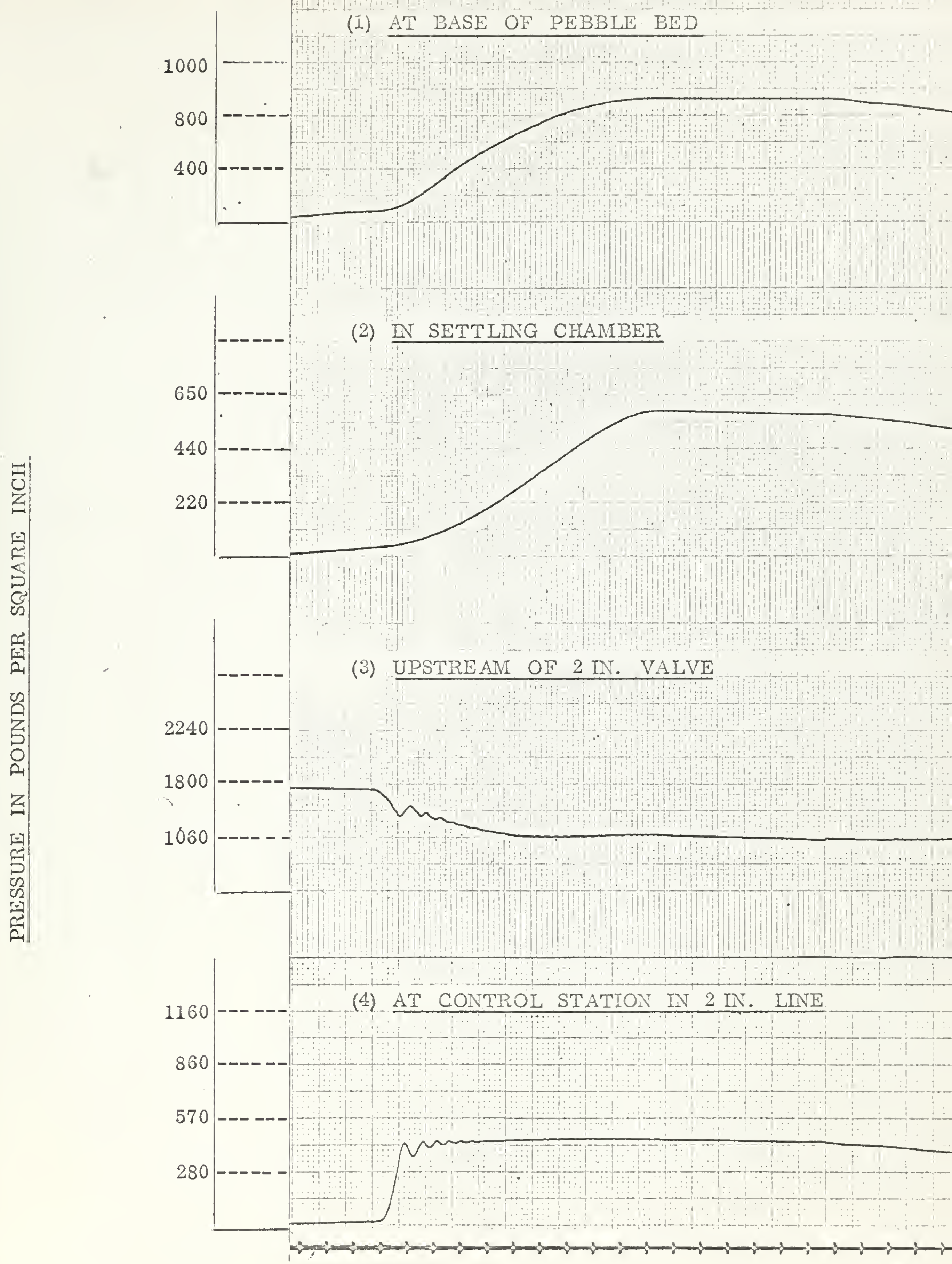


Figure 11 f

Pressure Response Data Using the Controller with Control Set-Point: 550 p.s.i.
Set-Point Adjuster: 0 Volts
Pebble Bed Temperature: 800° F.

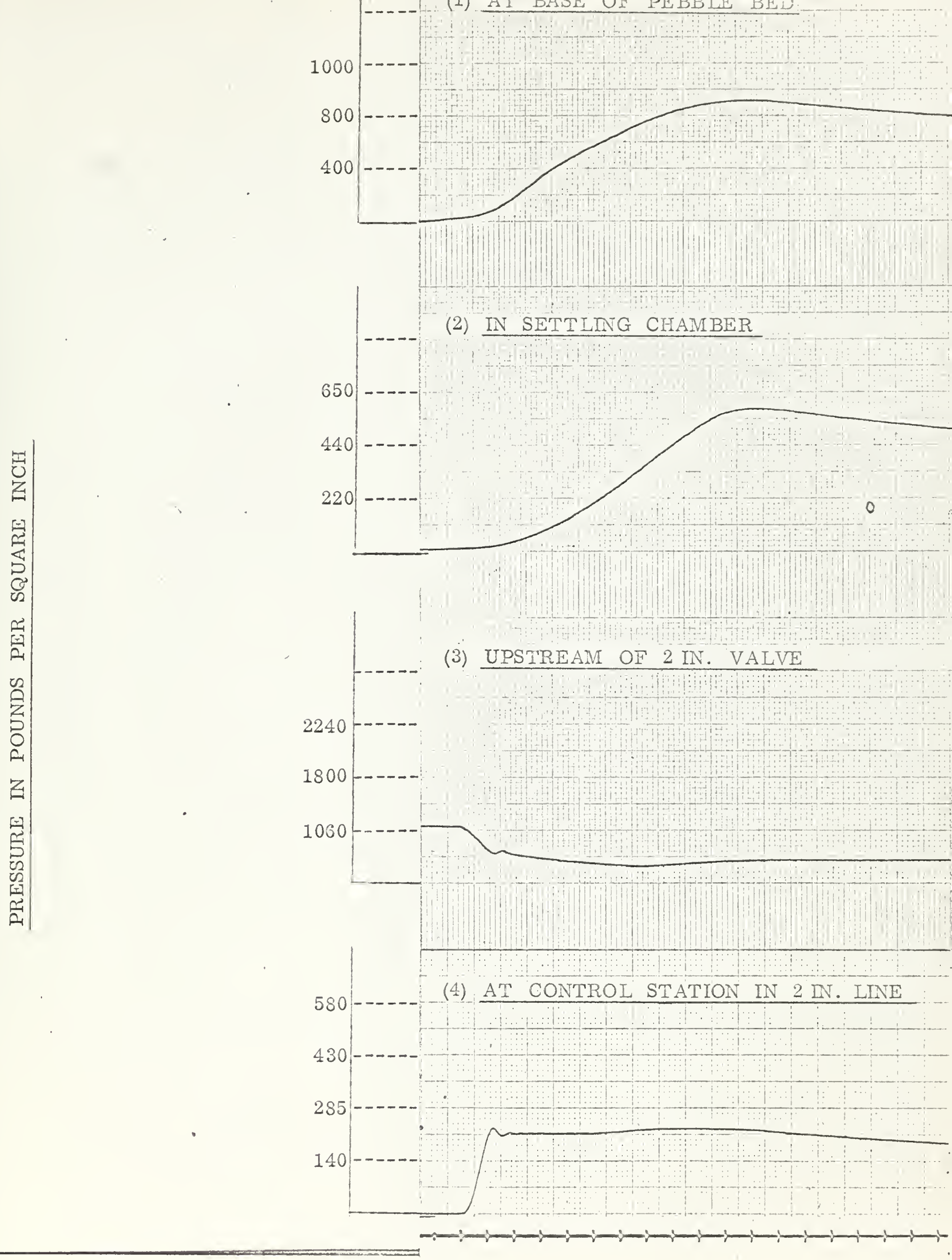


Figure 11 g

Pressure Response Data Using the Controller with Control Set-Point: 550 p.s.i.
Set-Point Adjuster: 0 Volts
Pebble Bed Temperature: 800° F.

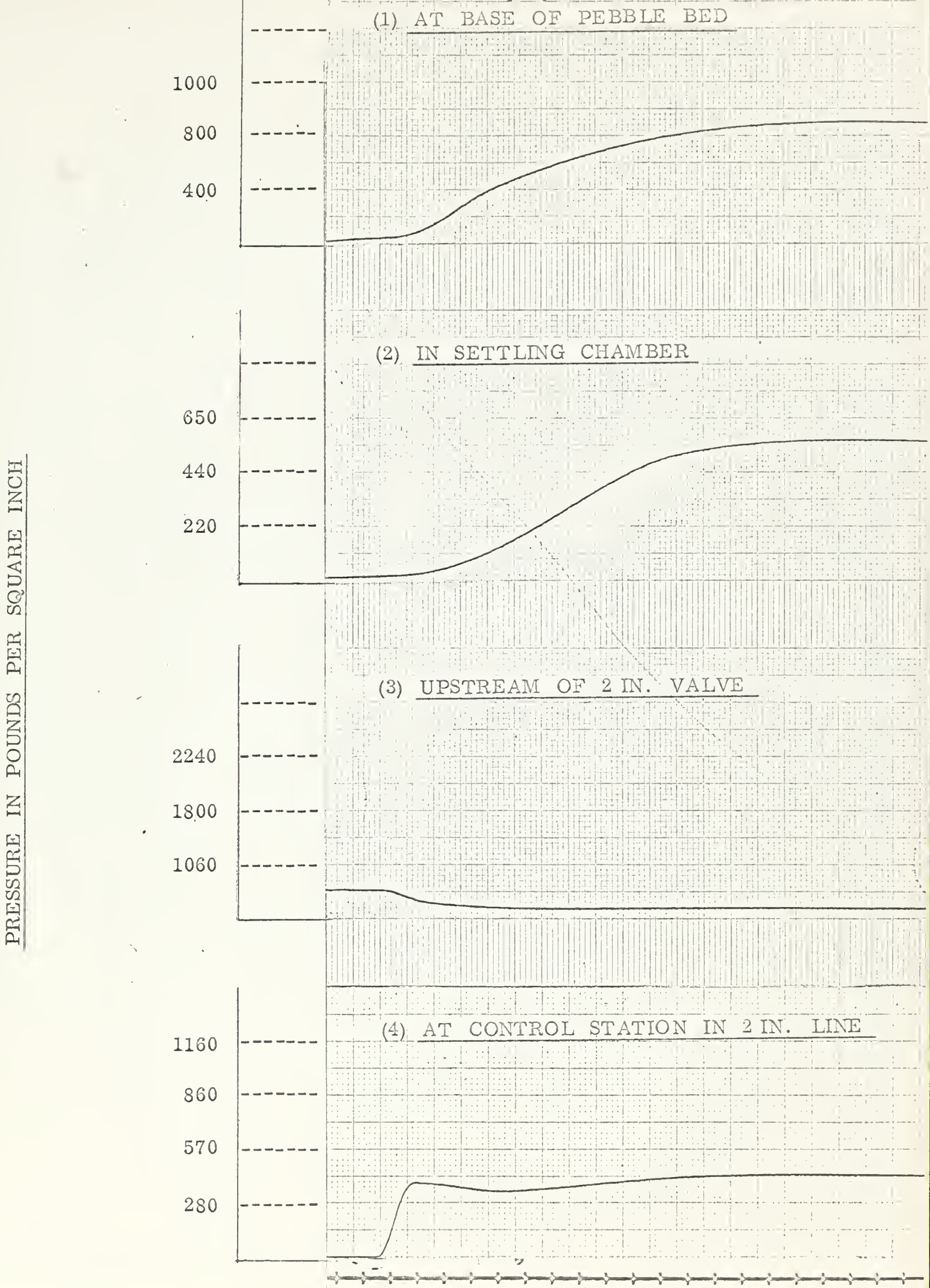


Figure 11 h

Pressure Response Data Using the Controller with Control Set-Point: 550 psi
Set-Point Adjuster: 0 Volts
Pebble Bed Temperature: 800°F.

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